A FACILITY FOR TESTING HIGH POWER DC, AC, OR PULSED DEVICES

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ABSTRACT

A fully instrumented facility being developed for the high power testing of pulsed-power and other devices is described. A bank of lead-acid batteries provides the facility with a power source having a maximum discharge capacity of 1.8×10^9 joules; the batteries can be switched into various series-parallel configurations to realize voltage-current combinations up to 10 kV at 250 A. The battery bank output terminals can be turned on and off at the test bench with a vacuum arc switch if desired. A high vacuum pumping station is built into the test bench for those devices requiring evacuation. An inverter using vacuum arc switches is being developed to convert the power to a sinusoidal AC source having a suitable frequency of up to 10 kHz. The battery bank operation is monitored and controlled either manually or by a microprocessor-based instrumentation system. The instrumentation system automates the battery charging cycle and shuts off the system whenever hazardous conditions develop in the facility during either the charge or the discharge cycle. Among the applications being investigated for the facility are the pulse and duration testing of vacuum arc switches and the development of a high-power inverter.

INTRODUCTION

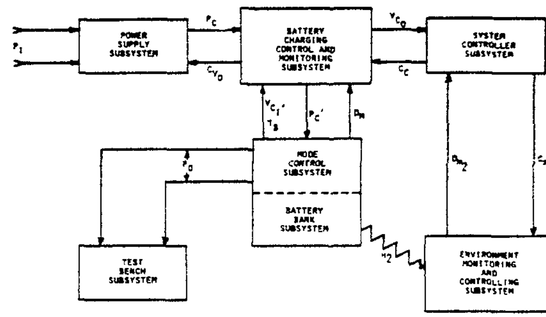
A high power inverter circuit employing vacuum arc switches (VAS's)[1,2,3] as the active devices is under development at the State University of New York at Buffalo (SUNYAB). This effort has progressed to the point that an unusually high-power dc source is now required to feed the inverter for advanced testing. Initially, this power source must be able to furnish 2.5 megawatts of power for two minutes, necessitating a usable 300 megajoule storage capacity.

A feasibility study[1] has shown that a facility capable of supplying the required dc power can be economically based on a system of interconnected lead-acid batteries. Such a system became even more practical when 91 dry-charged mine propulsion batteries were acquired by SUNYAB from Federal excess property listings. Each of these batteries produces 103.5 volts and approximately 50 ampere-hours, and the basis for the high-power dc test facility was at hand.

The following paragraphs contain discussions of the design and construction of this test facility, including safety and control precautions. The current state of development of the facility is given, and applications other than the testing of the VAS inverter circuits are listed.

BASIC DESCRIPTION OF THE HIGH-POWER DC TEST FACILITY

Figure 1 shows a functional block diagram of the high power test system. Its overall operation will be described in this section, and a more detailed discussion of the contents and operation of each block will appear in succeeding sections.



C_C - Control signals

C_F - Exhaust fan control signals

C_{V_O} - Charging voltage control signal

D_{H_2} - Information on hydrogen concentration

D_M - Information on operating mode in use

H_2 - Hydrogen from batteries

P_C - Battery charging power

P_C' - Regulated battery charging power

P_I - Input power (230 V, 188 A, 60 Hz, 3-phase)

P_O - Battery output power

T_B - Battery temperature

V_{C_i} - Voltage of the i-th cell

V_{C_O} - Transduced data signals

FIG. 1. THE SUNYAB/AFAPL* HIGH-POWER DC TEST SYSTEM

The Battery Bank Subsystem in its final form is to be composed of 96 of the mine propulsion batteries mentioned in the Introduction; this assemblage is capable of producing a total of 2.5 megawatts for at least two minutes, which supplies the 300 megajoules required. These batteries are interconnected in various configurations by the Mode Control Subsystem to produce either of the two basic modes, charging the batteries or discharging them.

In the charging mode, the Mode Control Subsystem connects all 96 of the batteries in parallel and connects them, each through its own individual charge current regulator circuit,

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14. ABSTRACT
A fully instrumented facility being developed for the high power testing of pulsed-power and other devices is described. A bank of lead-acid batteries provides the facility with a power source having a maximum discharge capacity of 1.8 x 109 joules; the batteries can be switched into various series-parallel configurations to realize voltage-current combinations up to 10 kV at 250 A. The battery bank output terminals can be turned on and off at the test bench with a vacuum arc switch if desired. A high vacuum pumping station is built into the test bench for those devices requiring evacuation. An inverter using vacuum arc switches is being developed to convert the power to a sinusoidal AC source having a suitable frequency of up to 10 kHz. The battery bank operation is monitored and controlled either manually or by a microprocessor-based instrumentation system.

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to the Power Supply Subsystem. In the discharge mode, the batteries are switched into any one of five series-parallel configurations to provide the desired voltage-current combination for testing some device at the Test Bench Subsystem.

During both basic modes the voltage of each cell and the temperature of each battery are monitored by the System Controller Subsystem through the Battery Charge Control and Monitoring Subsystem. When the batteries are charging, the System Controller Subsystem selects the optimum charge rate for each battery and continuously searches for abnormal temperature and voltage conditions which would indicate a deteriorating battery or cell. Any abnormalities are recorded on a printer and are then checked out manually. As each battery reaches full charge, the System Controller Subsystem disconnects it from the charging circuit, and when all batteries have been charged the System Controller Subsystem turns off the Power Supply Subsystem.

When the batteries are discharging, the purpose of the voltage and temperature monitoring becomes precautionary; if a failure begins to occur, as indicated by an abnormal cell voltage or battery temperature, the discharge is interrupted until the problem can be eliminated. During both the charge and discharge cycles, the Environment Monitoring and Controlling Subsystem provides a means of monitoring the concentration of hydrogen in the room containing the batteries. This room is continuously exhausted by fans during charging or discharging, but if the hydrogen concentration approaches explosive levels, the System Controller Subsystem interrupts the cycle until the concentration is brought to a safe level.*

The Test Bench Subsystem is designed for flexibility so as to meet the needs of most devices that might be tested. A high vacuum pumping station is provided, as is most electronic test equipment that might be needed. A vacuum arc switch provides the device being tested with either pulsed or continuous power as might be needed, and a variable frequency inverter circuit provides for the testing of high power ac devices. A voltage doubler circuit provides a higher voltage, low current source when required.

A lower power, capacitive discharge pulse system is also available for alternate low power pulse testing.

Thus a highly automated test facility is under development. A more detailed description of each subsystem now follows.

THE BATTERY BANK SUBSYSTEM

Figure 2 shows one of the lead-acid batteries as it was received. This battery consists of 48 dry-charged cells which, when filled with electrolyte having a specific gravity of 1.315 (required by the manufacturer), should yield an open-circuit voltage of approximately 103.5 volts[4,5]. Tests performed indicate agreement to within one per cent of this value for each of 12 batteries.

Each of the batteries is modified as shown in Figure 3 to permit the voltage of each cell to be measured at a location remote to the battery. This modification also permits the batteries to be hung in specially constructed racks as shown in Figure 4.

* Vinal[4] says a 4 percent mixture of hydrogen in the air is dangerous, and that the mixture should not be permitted to exceed 2 percent.

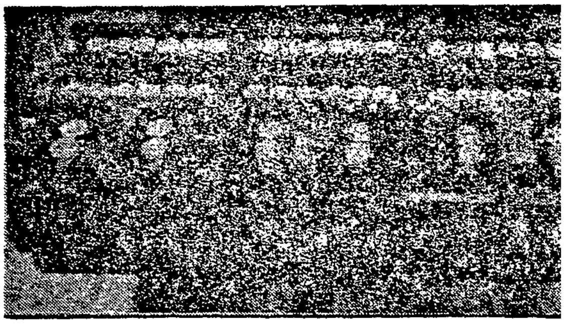


FIG. 2. MINE PROPULSION BATTERY

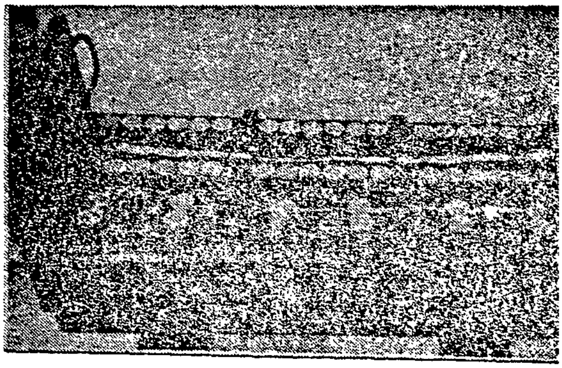


FIG. 3. THE MODIFIED MINE PROPULSION BATTERY

In order to be able to determine the characteristics of any device being tested, the characteristics of the entire power-delivering system must be known. To characterize each battery, the model shown in Figure 5[6] was chosen. Initial tests have yielded the parameter values indicated.

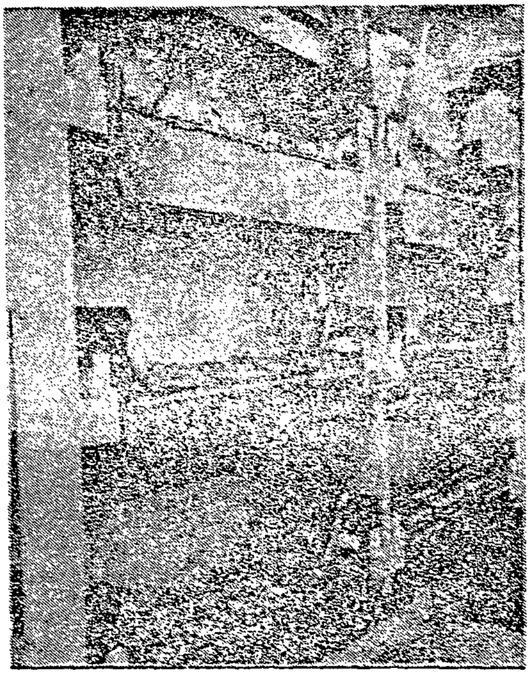
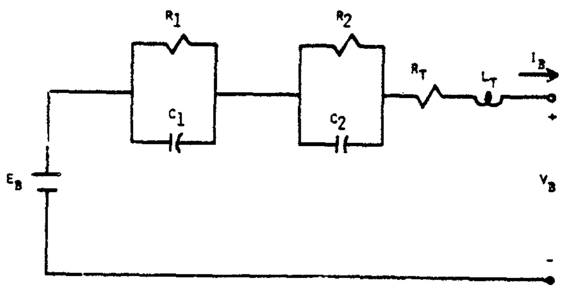


FIG. 4. MINE PROPULSION BATTERIES MOUNTED IN RAC



E_B - 103.5 V

R_1 - 0.04 mΩ

C_1 - 25 600 F

R_2 - 0.04 mΩ

C_2 - 25 600 F

R_T - 0.22Ω

L_T - 0.42 μH

FIG. 5. A MODEL FOR THE MINE PROPULSION BATTERY

THE MODE CONTROL SUBSYSTEM

As indicated in the section concerning the basic description of the test facility, the principal functions of the Mode Control Subsystem are to connect the batteries (1) to the Power Supply Subsystem so that the batteries can be charged or (2) in such a configuration that the desired voltage-current combination can be supplied to the test bench. Thus the Mode Control Subsystem is primarily a system of switches and interconnected cables which will connect the desired configuration.

The diagram in Figure 6 shows the switching combinations that are available. In the 96 X 100 mode the batteries are all connected in parallel for charging. The charging cycle is explained in a later section.

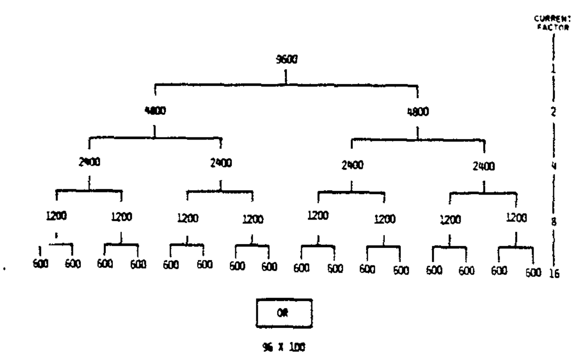


FIG. 6. BATTERY SWITCHING MODES

All batteries are connected in series in the 9600 mode; assuming each battery has a conducting terminal voltage of 100 volts, this mode produces 9600 volts and a normalized current factor (CF*) of 1. The 4800 mode is achieved by connecting two series strings of 48 batteries in parallel, providing 4800 volts and a CF of 2 at the test bench.

* The CF is the maximum current available at the test bench divided by the maximum current available from one battery.

The 2400, 1200 and 600 modes are explained in a similar manner.

A further inspection of Figure 6 shows that the basic voltage element (BVE) during discharge is an assemblage of six batteries connected in series, yielding a nominal 600 volts. All discharge modes can be realized by combining BVE's in series and/or parallel. Therefore, the intraconnections for all 16 BVE's are the same and are shown in Figure 7; Figure 8 shows the prototype series-connecting switches for a BVE. The series regulators shown disconnected in Figure 7 are part of the Battery Control and Monitoring Subsystem and their control is explained in the section describing that subsystem.

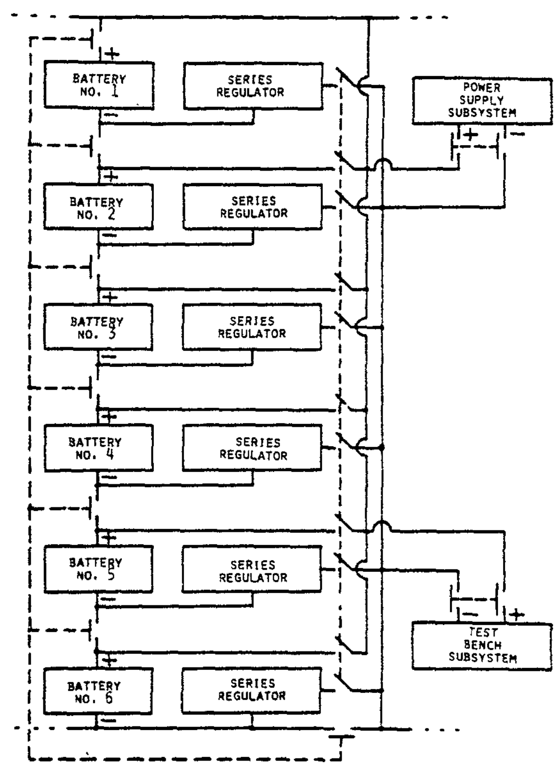


FIG. 7. THE 600-VOLT BASIC VOLTAGE ELEMENT (BVE)

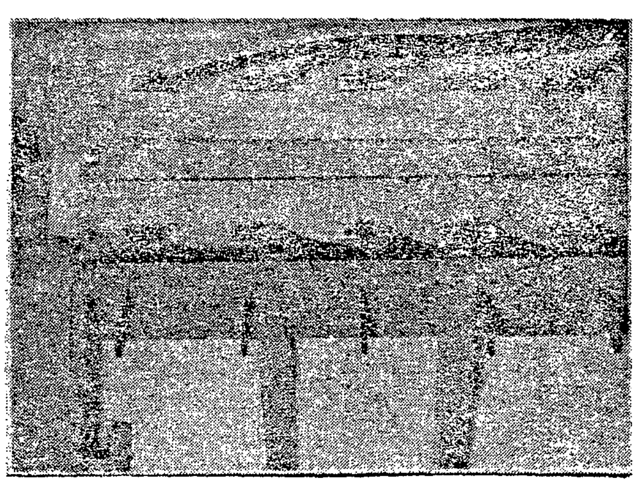


FIG. 8. SERIES-CONNECTED SWITCHES FOR A BVE

THE POWER SUPPLY SUBSYSTEM

Information supplied by the manufacturer about the batteries indicates that the cells should never be discharged below a 1.67 volt level, or 80 volts at the terminals. The manufacturer further recommends a charging rate of 2 amps for terminal voltages below 108 volts, and a finishing rate of 1 amp above 108 volts until the battery is fully charged, which yields a final terminal voltage on charge of nearly 140 volts.

Assuming that the manufacturer's recommended discharging parameters are followed such that the batteries are never discharged below 80 volts, the Power Supply Subsystem must be able to furnish a maximum charging current of 192 amps (at 2 amps per battery) over a Battery Bank Subsystem terminal voltage range from 80 to 108 volts and a maximum charging current of 96 amps (at 1 amp per battery) over a voltage range from 108 volts to 140 volts.

The power supply shown in Figure 9 satisfies these requirements. It is an extreme duty welding power supply

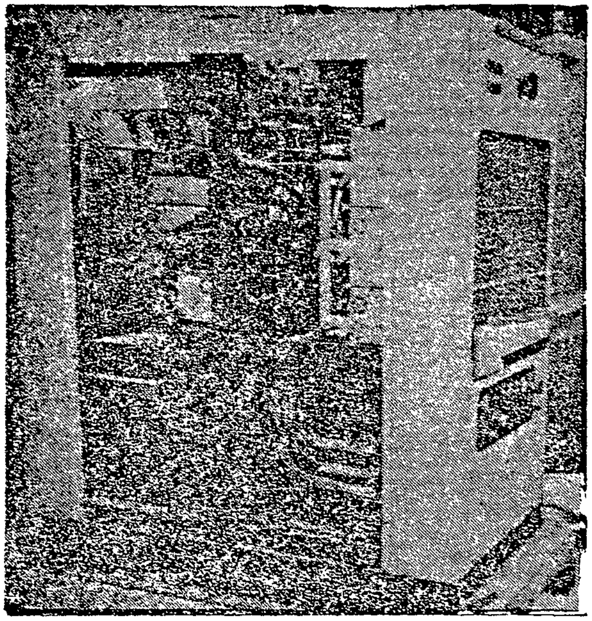


FIG. 9. THE POWER SUPPLY SUBSYSTEM

whose operating parameters are shown in Figure 10. Once the charge cycle has been initiated, the power supply is controlled by the System Controller Subsystem, including automatic shutoff at the end of the charge cycle.

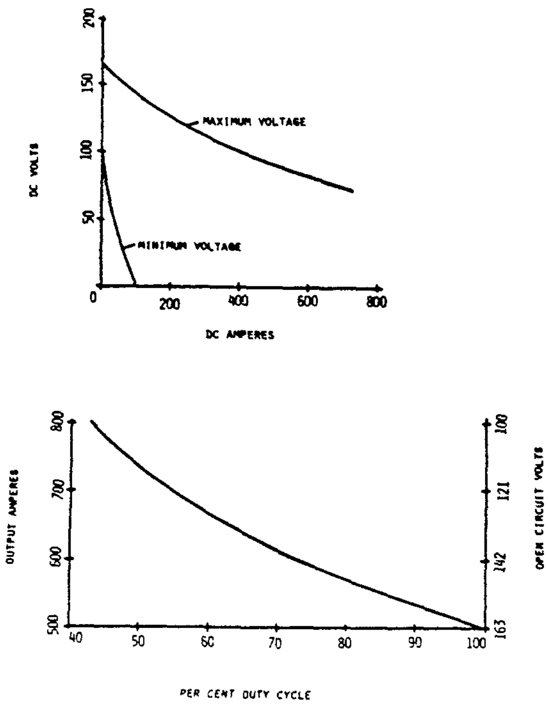


FIG. 10. POWER SUPPLY SUBSYSTEM OPERATING CHARACTERISTICS

Figure 11 shows the connections to the microcomputer The keyboard and video display provide the primary m machine interface for program development and system inquiry. The printer provides hard copy of programs and is used by the microcomputer for data logging. Tl cassette tape unit provides mass storage during program development and stores data for processing at a

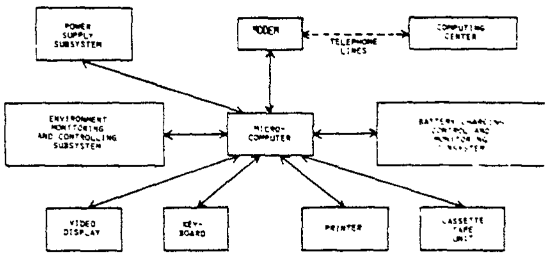


FIG. 11. THE SYSTEM CONTROLLER SUBSYSTEM

later time. The modem provides a low speed data lin via telephone lines to a computing center where complex processing of data takes place. The link to th Environment Monitoring and Controlling Subsystem is for monitoring the hydrogen concentration in the roo containing the Battery Bank Subsystem and for turnin the exhaust fans on or off as required. The connection to the Battery Charging Control and Monitoring Subsystem represents the many high speed data channe used to send control information to and receive data from the Battery Bank Subsystem. This link is described in more detail in the following section. The Power Supply Subsystem connection permits automatic control of the power supply during the charge cycle.

THE SYSTEM CONTROLLER SUBSYSTEM

The essential system controller is a microcomputer[6] consisting of read-write memory used for temporary data storage and program development. Programmable read only memory is used for the permanent storage of programs which have been developed and tested. A mine propulsion battery, under constant charge, supplies power to the System Controller Subsystem.

The microcomputer's serial and parallel input-output ports provide communications channels with the rest of the System Controller Subsystem as well as with the other subsystems in the facility.

The System Controller Subsystem thus provides for the automatic control of the facility, freeing otherwise attending personnel for more constructive roles. This approach is not without flexibility, however, as changes in the controlling algorithm are easily made by making appropriate changes to the program stored in the microcomputer's memory.

BATTERY CHARGING CONTROL AND MONITORING SUBSYSTEM

The Battery Charging Control and Monitoring Subsystem provides a means of (1) collecting data from each battery concerning its temperature and the voltage of each of its cells and passing that data to the System Controller Subsystem, and (2) distributing the charging commands to the appropriate series regulator to meet the individual charging demands of each battery.

At the highest level of control in this subsystem is the Battery Bank Communications Unit. This unit, for which the block diagram is shown in Figure 12 is the interface between the microcomputer in the System Controller Subsystem and each of the Basic Voltage Element (BVE) Communications Units. The Battery Bank Communications Unit converts parallel data from the microcomputer to serial data and sends this data over 16 duplex data channels to the 16 BVE Communications Units. This process is reversed for serial data being sent from the BVE Communications Units to the microcomputer. Each of the 16 duplex data channels con-

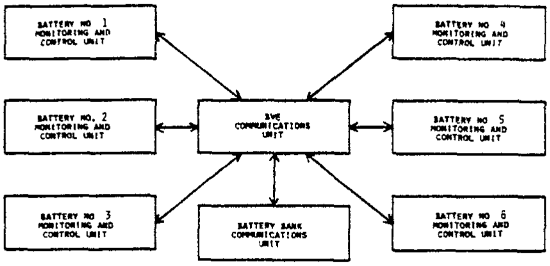


FIG. 12. THE BATTERY BANK COMMUNICATIONS UNIT BLOCK DIAGRAM

sists of two fiber optic cables, permitting full bidirectional serial data transmission and electrically isolating the microcomputer from the high dc voltages in the Battery Bank Subsystem.

The BVE Communications Unit, shown in block diagram form in Figure 13, distributes battery charge rate commands during the battery charging cycle and sensor addresses from the microcomputer to the Battery Monitoring and Control Unit located with the series regulator circuit at each of the six batteries in the BVE. The BVE Communications Unit also collects multiplexed analog sensor voltages form each battery, converts these voltages to digital form, and transmits the resulting digital signals to the Battery Bank Communications Unit. These functions are all controlled by commands from the microcomputer.

The Battery Monitoring and Control Unit is at the lowest level in the control hierarchy. This unit directly interfaces the battery to the BVE Communications Unit, as shown in Figure 14. The lowest level control functions include setting the battery charge rate to selected values and sampling and analog multiplexing all cell voltages and temperature sensor output voltages down to one line going to the BVE Communications Unit. The level shift circuitry and isolators are basically optical isolators, and the circuits of this unit are powered by the battery they control.

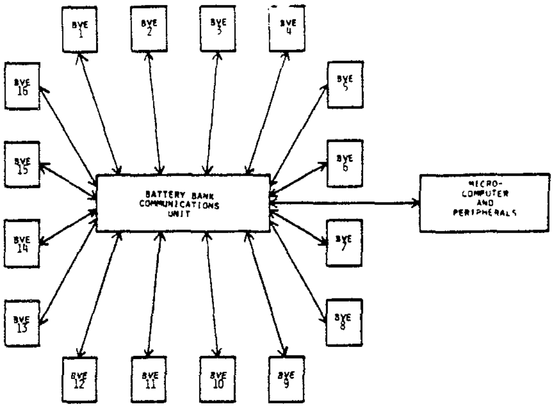


FIG. 13. THE BASIC VOLTAGE ELEMENT COMMUNICATIONS UNIT BLOCK DIAGRAM

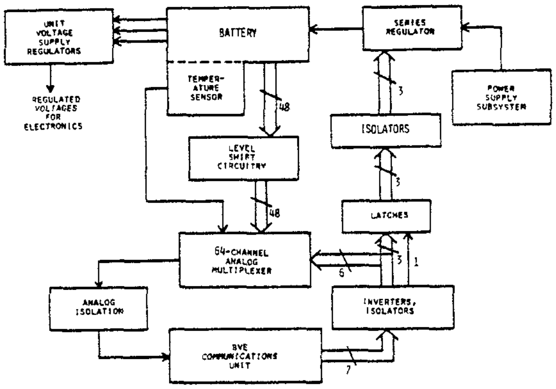


FIG. 14. THE BATTERY MONITORING AND CONTROL UNIT BLOCK DIAGRAM

The Battery Charging Control and Monitoring Subsystem is thus the key element in interfacing the controlling microcomputer with the battery bank.

THE ENVIRONMENT MONITORING AND CONTROLLING SUBSYSTEM

The Environment Monitoring and Controlling Subsystem consists of a hydrogen detector and two sparkless 1000 CFM exhaust fans. Figure 15 shows their connection

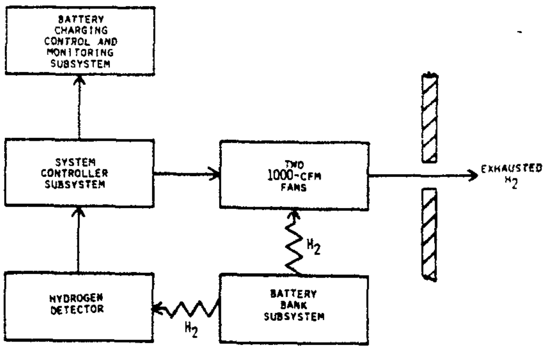


FIG. 15. THE ENVIRONMENT MONITORING AND CONTROLLING SUBSYSTEM BLOCK DIAGRAM

with the microcomputer, which gathers hydrogen concentration data from the hydrogen detector. If the facility is in either the charge or discharge cycle the microcomputer turns on one fan. If the hydrogen concentration reaches one percent the microcomputer turns on the second fan, which is turned off when the concentration drops below 0.9 percent. However, should the concentration reach 1.9 percent the microcomputer interrupts the facility cycle until the concentration drops below 1.4 percent.[4]

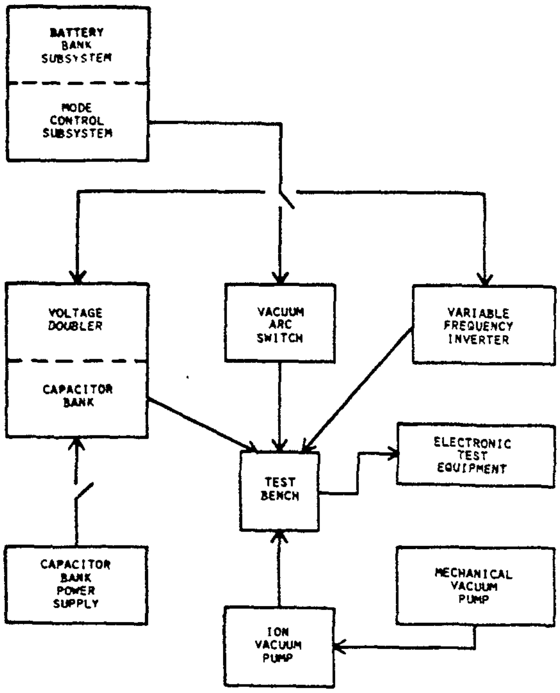


FIG. 16. THE TEST BENCH SUBSYSTEM BLOCK DIAGRAM

THE TEST BENCH SUBSYSTEM

Figure 16 depicts the Test Bench Subsystem. Power is fed to the Test Bench Subsystem from the Battery Bank Subsystem via the Mode Control Subsystem. Power at the test bench is delivered either through a capacitor bank, through vacuum arc switch or through a variable frequency inverter, the choice depending on the power waveform desired. The capacitor bank can be used either as a storage device, in conjunction with the battery bank, to provide voltage doubling capability or as a capacitive discharge pulsing system. In this letter mode the capacitor bank can be operated off a separate 5 kV, 10A power supply. The vacuum arc switch can provide continuous or pulsed power, while the inverter is capable of furnishing a sinusoidal current at frequencies up to 10 kilohertz.

The vacuum equipment provides for testing in an evacuated environment if required, and the test equipment provides full instrumentation capabilities.

STATE OF DEVELOPMENT

The facility is currently being used to provide 10 kilowatts of power for continuous testing of the inverter circuit described in the preceding section, and can provide up to 325 kilowatts for a two minute period. A power expansion up to 1.25 megawatts is planned by March 1, 1977, with further development to the 2.5 megawatt level by September, 1977.

Control of the charge and discharge cycles is now manual, the construction of the Battery Charging Control and Monitoring Subsystem and System Controller Subsystem having just begun. It is anticipated this construction will keep pace with the construction of the remainder of the facility.

APPLICATIONS

As implied by the preceding sections, this test facility is intended to provide a broad capability for testing high power devices in several modes. At present testing is beginning on a high power inverter[1] and duration testing of a vacuum arc switch is planned to begin in the near future.

REFERENCES

1. A. S. Gilmour, Jr. and D. L. Lockwood, "Vacuum arc inverter switch development program," Proc. IEEE 1975 NAECON, pp. 281-288, June 1975.

2. A. S. Gilmour, Jr. and D. L. Lockwood, "Pulsed metallic-plasma generators," Proc. IEEE, vol. 60, pp. 977-991, August 1972.

3. A. S. Gilmour, Jr. and D. L. Lockwood, "The interruption of vacuum arcs at high dc voltages,' IEEE Transactions on Electron Devices, April 197

4. G. W. Vinal, Storage Batteries, third edition, John Wiley and Sons, 1940.

5. J. W. Beck et al, "A computer study of battery energy storage and power conversion equipment operation," IEEE Transactions on Power Apparatus and Systems, July/August, 1976.

6. D. G. Fink and J.M. Carroll (ed.), Standard Hand book for Electrical Engineers, tenth edition, McGraw-Hill, 1968.

7. S. P. Perone and D. O. Jones, Digital Computers in Scientific Instrumentation, McGraw-Hill, 1973